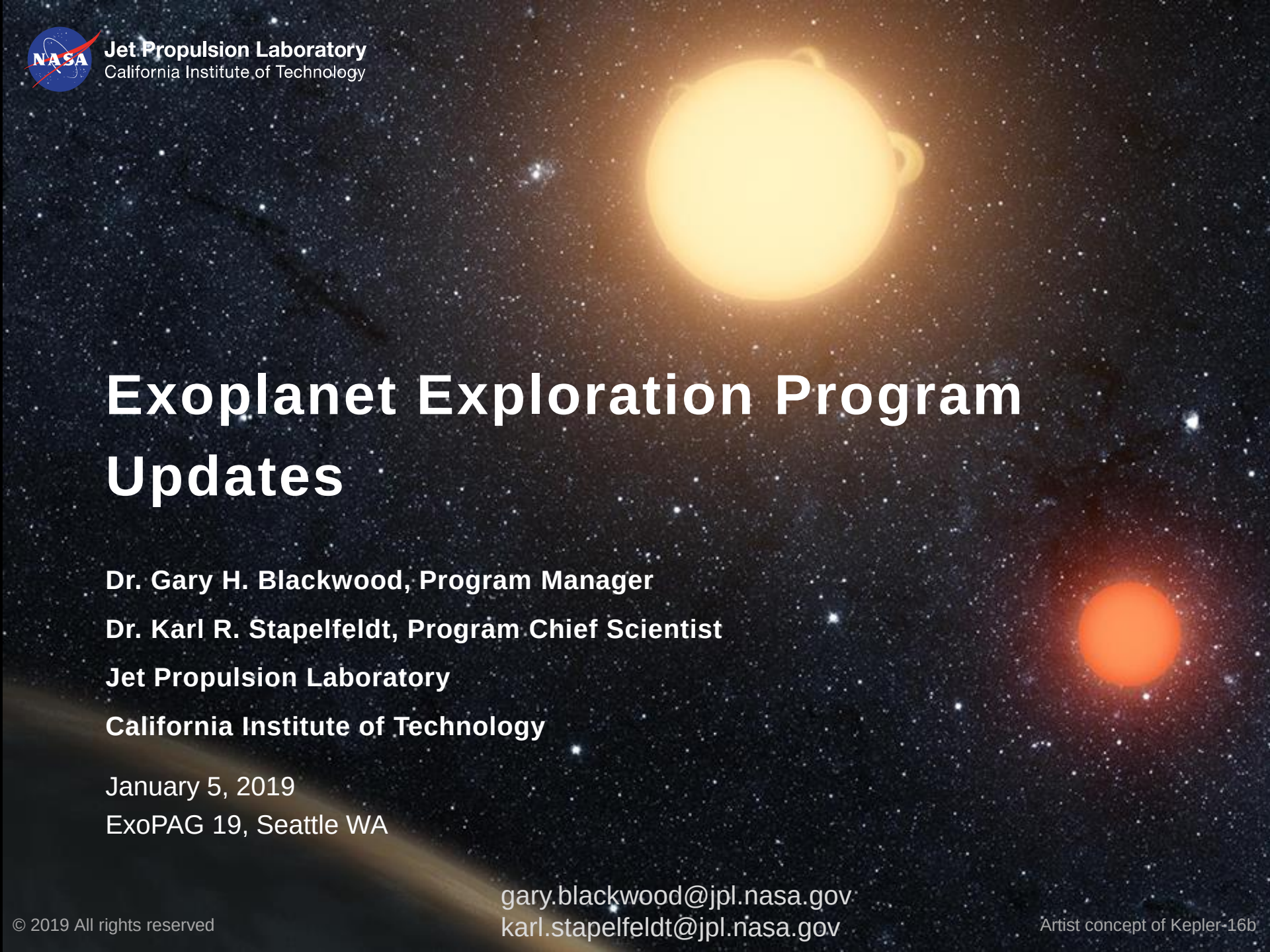


Jet Propulsion Laboratory
California Institute of Technology

Exoplanet Exploration Program Updates

Dr. Gary H. Blackwood, Program Manager

Dr. Karl R. Stapelfeldt, Program Chief Scientist

Jet Propulsion Laboratory

California Institute of Technology

January 5, 2019
ExoPAG 19, Seattle WA

gary.blackwood@jpl.nasa.gov
karl.stapelfeldt@jpl.nasa.gov

Artist concept of Kepler-16b

Program Overview

Responses to ExoPAG Suggestions

Implementation Updates

LBTI Science

Program Science Updates

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

NASA's search for habitable planets and life beyond our solar system

Program purpose described in 2014 NASA Science Plan

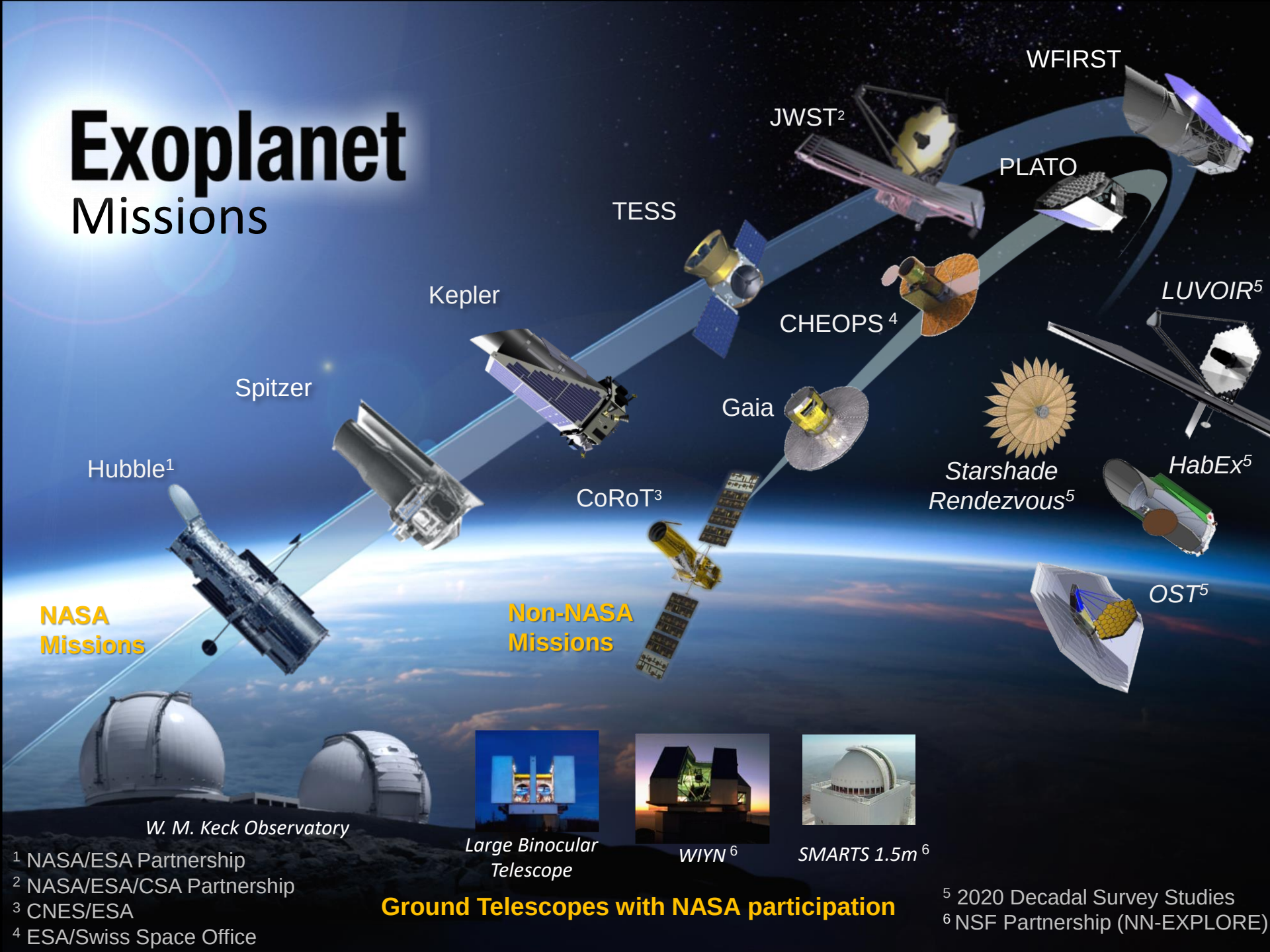
1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

ExEP serves the Science Community and NASA:

- Focal point for exoplanet science and technology
- Integrates cohesive strategy for future discoveries

https://exoplanets.nasa.gov

Exoplanet Missions



Ground Telescopes with NASA participation

[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
[4] ESA/Swiss Space Office
[5] 2020 Decadal Survey Studies
[6] NSF Partnership (NN-EXPLORE)

NASA Exoplanet Exploration Program

Space Missions and Concept Studies

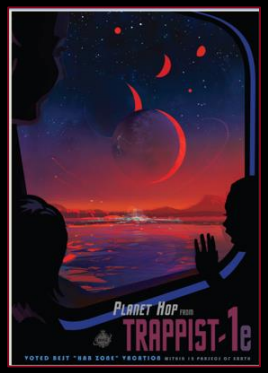
Kepler K2

Large- and Probe-Scale Mission Concepts

Coronagraph

Starshade

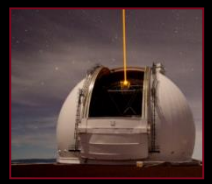
Exoplanet Communications



Science Research & Technology

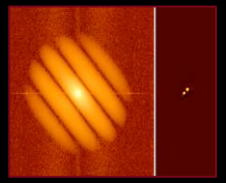
Key Sustaining Research

NN-EXPLORE



Keck Observatory

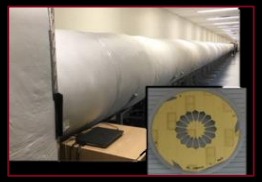
Large Binocular Telescope Interferometer



High Resolution Imaging

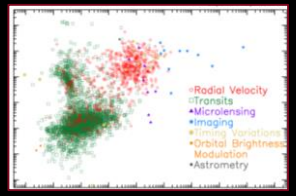
Technology Development

Coronagraph Technology Development



Starshade Technology Development (S5)

NASA Exoplanet Science Institute (NExScI)



Archives, Tools, Sagan Program, Professional Engagement

Some of other Services Provided by ExEP

As chartered by NASA Astrophysics

- Recommend to APD strategies to advance NASA's exoplanet science and technology objectives
  - Informed by missions, academy reports, and ExoPAG
- Conduct mission studies and trades
- Capture and maintain technology roadmaps
- Technology: identify, prioritize, manage, and certify TRL
- Engage in non-APD and non-NASA partnerships
- Facilitate the ExoPAG

- In all cases: Decisions guided by science priorities

Program Overview

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LBTI Science

Program Science Updates

Responses to ExoPAG Suggestions

In the Short Term

- Added links of "NASA Funded Exoplanet Opportunities"
  - to https://exoplanets.nasa.gov/exep/resources/links/
- Demographics SIG2 approved by APAC
- WFIRST CGI PSP – opportunity to join Participating Science Program (see D. Benfored, HQs)
- Increased communication timeliness and content through exopagannounce mailing list (Mamajek)
- Responsive to agenda requests for ExoPAG

Responses to ExoPAG Suggestions

In the Long Term: Continuing, and Portfolio Adjustments

- Continue ExoPAG student/postdoc session
  - Congratulations to Carl Coker, Eliot Vrijmoet, Leonardo Paredes, and Maggie Thompson
- Continue ExEP Staff – resource availability to community (e.g. Lynx trade study, in-Space Assembled Telescopes)
- Precision Radial Velocity discussions with HQ following NAS ESS report
- Maintain and expand exoplanet archive
- Increased observation opportunities and community access to data (following slide)

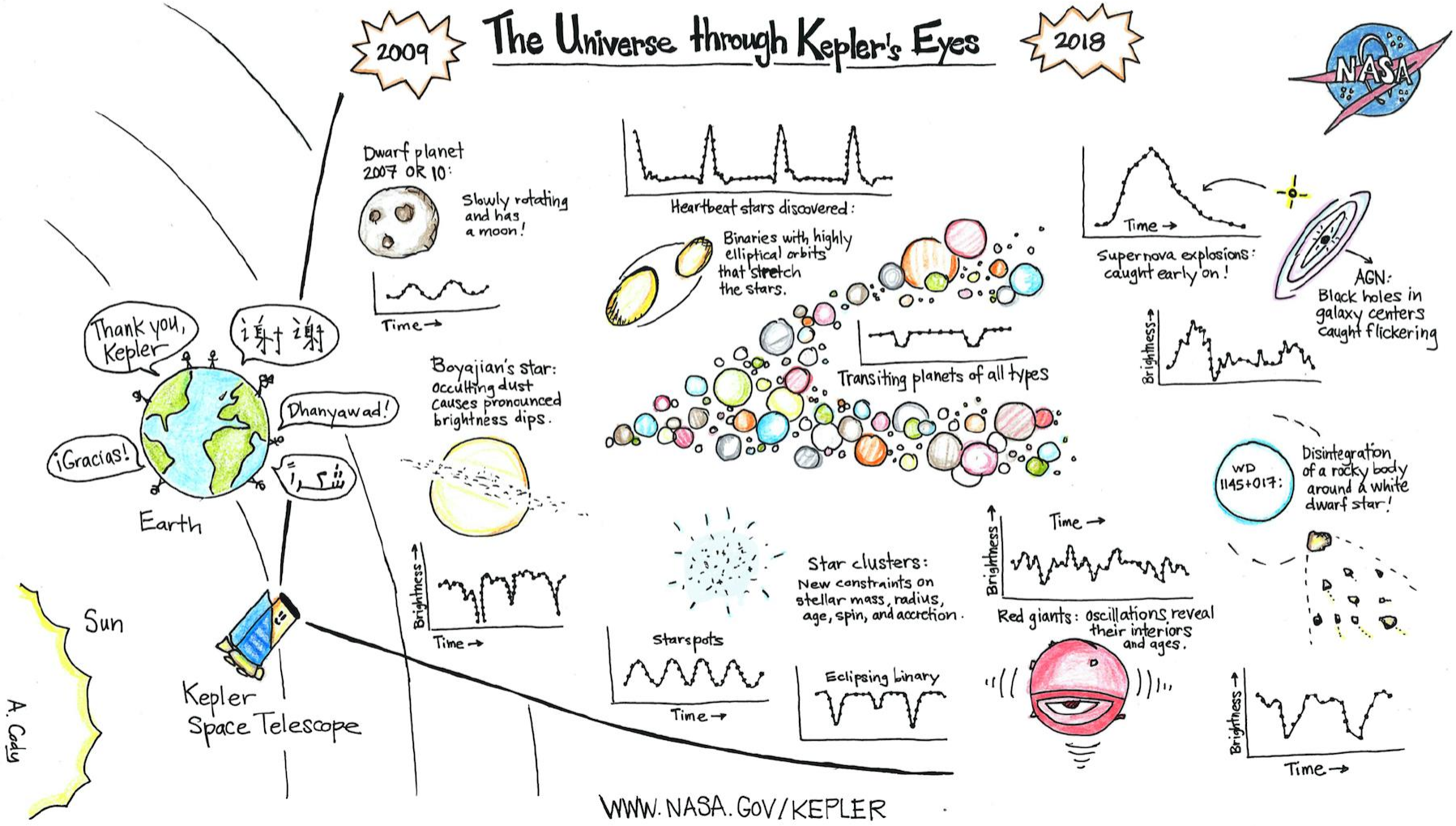
Exoplanet Travel Bureau "Study Abroad" edition

Increased Observation Opportunities

And Community Access to Data

- WIYN / NEID: call for 2019B semester will be upcoming NOAO call for 2019B (~March 2019)
- CHIRON on SMARTS 1.5m telescope: US access to southern hemisphere RV:
  - 40 nights/semester
  - Complements Keck / HIRES and WIYN / NEID
- Keck Special Projects included in TBD call
- Community access to High Resolution Imaging - Speckle
  - Three instruments available through NOAO: WIYN/NESSI (39 mas), Gemini-N/'Alopeke and Gemini-S/DSSI (17 mas)
  - Data processed by PI team and posted at NExScI archive
- Community Access to HIRES PRV data reduction pipeline
- K2 (re) processed data available at MAST

New cartoons submitted to PAO



Kepler K2

- End of Flight due to fuel exhaustion
- Goodnight command sent on Nov. 15th, Johannes Kepler's death anniversary
- C19 (partial) data downlinked.
- Data Processing
  - C0 to C18 data at MAST. C19 data processing underway. Raw cadence online
- Data reprocessing: C0, C2, C3, C13. Next is C11
- Kepler/K2 SciCon V
  March 4-8, 2019; Glendale CA

Program Overview

Responses to ExoPAG Suggestions

Implementation Updates

LBTI Science

Program Science Updates

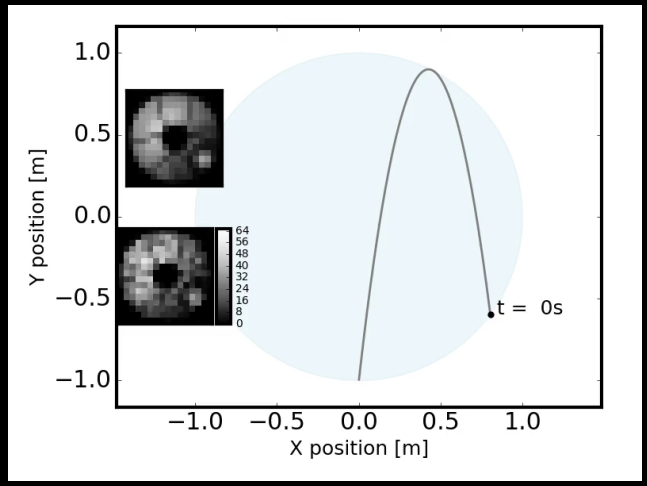
Program Highlights

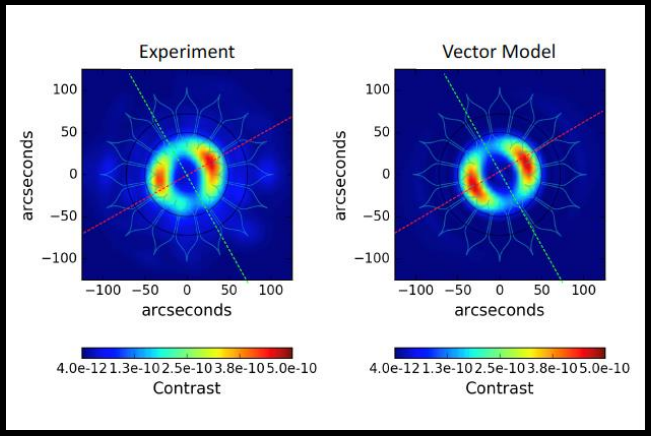
- LBTI: completed survey, studying instrument upgrades
- Technology:
  - Ccoordination with PCOS/COR programs
  - Decadal Survey Testbed: Lyot coronagraph 4e-10 contrast
  - Segmented Coronagraph Design: results adopted by LUVOIR
- Support to WFIRST: MEMs defTechnology ormable mirrors, coronagraph testing, starshade interface
- Support to Large Mission Studies and Probe Studies
- NExScI: Exoplanet archives, Sagan Summer Workshop
- Follow-up Observing site provide to TESS by NExScI
- ExoComm: Exoplanet Travel Bureau immersive experience
- NEID: final integration and test underway at Penn State
- ExEP Postdoc position created
- Starshade Technology Development Plan and Partnership

Starshade Technology Development (S5)

Reach Technology Readiness Level 5

- Advances technologies of optical suppression, formation flying, and mechanical deployment
  - Highlights of 2018:
    - Technology plan released
    - Lateral position sensor testbed results meet formation flying performance requirements;
    - Subscale masks demonstrating 10^{-10} contrast performance in Princeton testbed
    - First article petal prototype assembled at Tencor
    - Developed starshade imaging tool





https://exoplanets.nasa.gov/exep/technology/starshade/

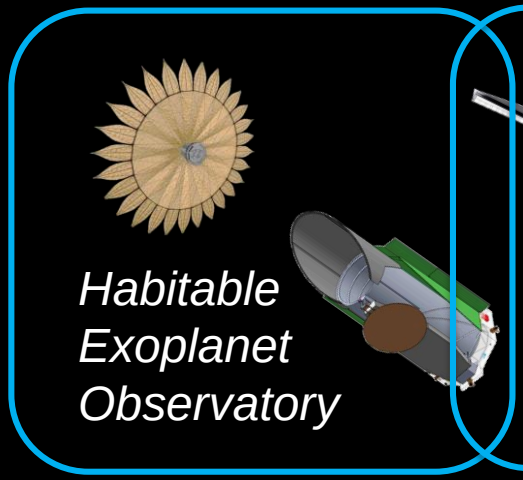
Starshade Science and Industry Partnership

- Purpose:
  - Maximize the technology readiness of starshades
  - Complement the work of S5 technology development
- Scope:
  - Up to 3 cost-sharing contracts, small business set-aside
  - Technology and Science Working Group
  - Support for graduate and postdoc participation
- Approach:
  - Bimonthly telecons
  - Semi-annual face-to-face starting July 2019
- To Learn more contact POC (Gary Blackwood) or visit: https://exoplanets.nasa.gov/exep/technology/starshade

See extensive notes in ppt for speaking

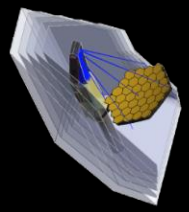
Mission Concepts for Decadal Su

Large Scale Mission Concepts

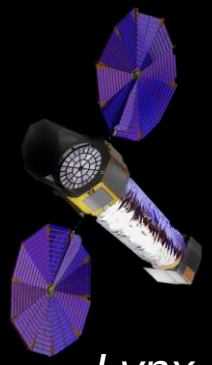


Habitable Exoplanet Observatory

LUVOIR



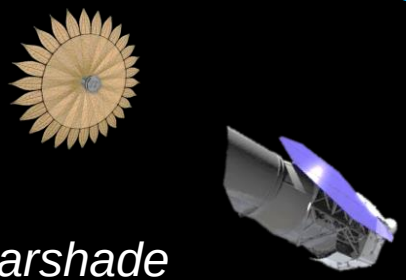
Origins Space Telescope



Lynx

Exoplanet Medium Scale Concepts

EarthFinder



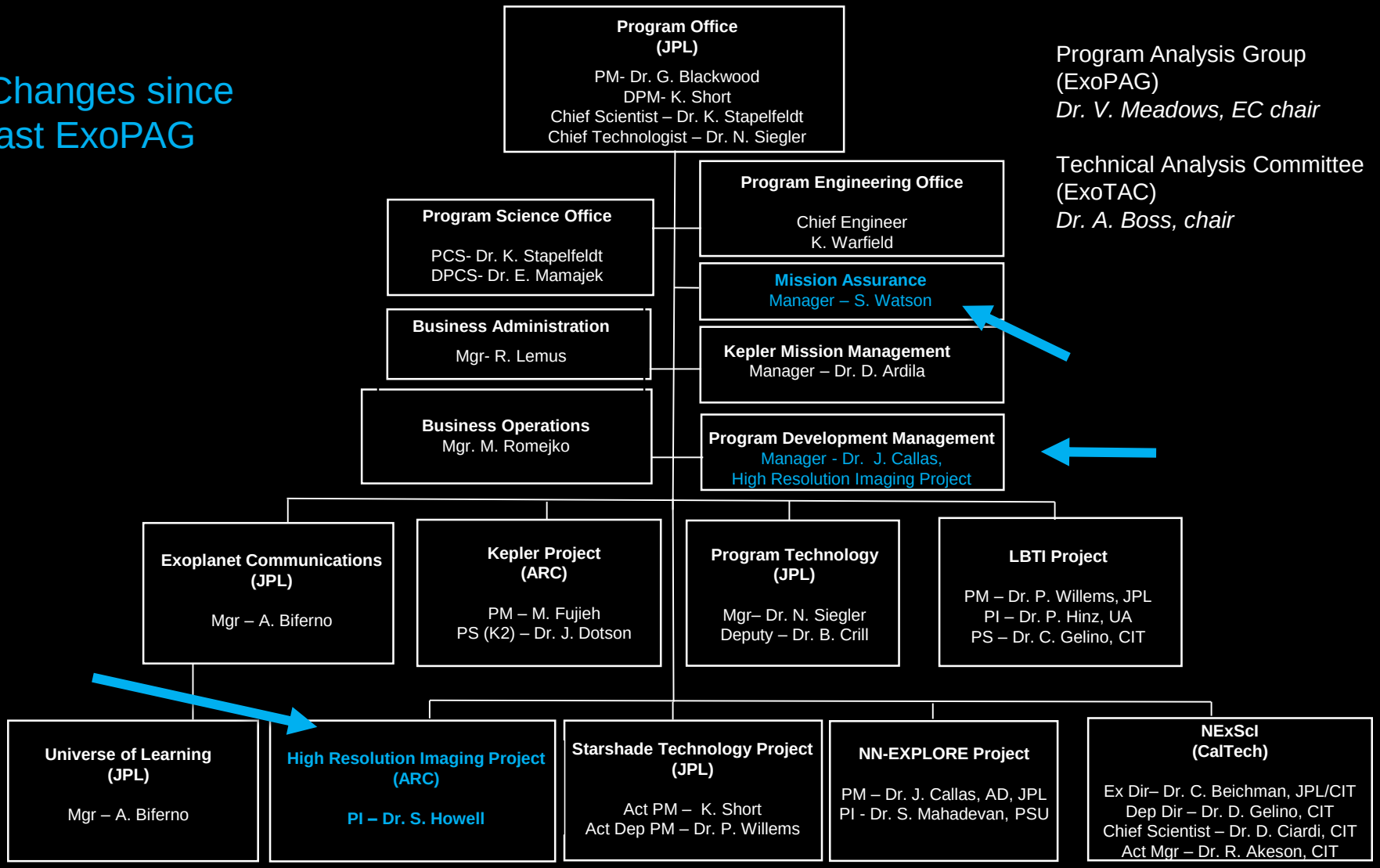
Starshade Rendezvous

https://science.nasa.gov/astrophysics

NASA Exoplanet Exploration Program

Astrophysics Division, Science Mission Directorate

Changes since last ExoPAG



Program Analysis Group (ExoPAG)
Dr. V. Meadows, EC chair

Technical Analysis Committee (ExoTAC)
Dr. A. Boss, chair

Stay Connected with ExEP:

Exoplanets.nasa.gov

Exopagannounce mailing list

StarshadeSIP mailing list

gary.blackwood@jpl.nasa.gov

karl.stapelfeldt@jpl.nasa.gov

Program Overview

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Implementation Updates

LBTI Science

Program Science Updates

Call for Proposals: NASA Keck time for Strategic Mission Support in 2019B

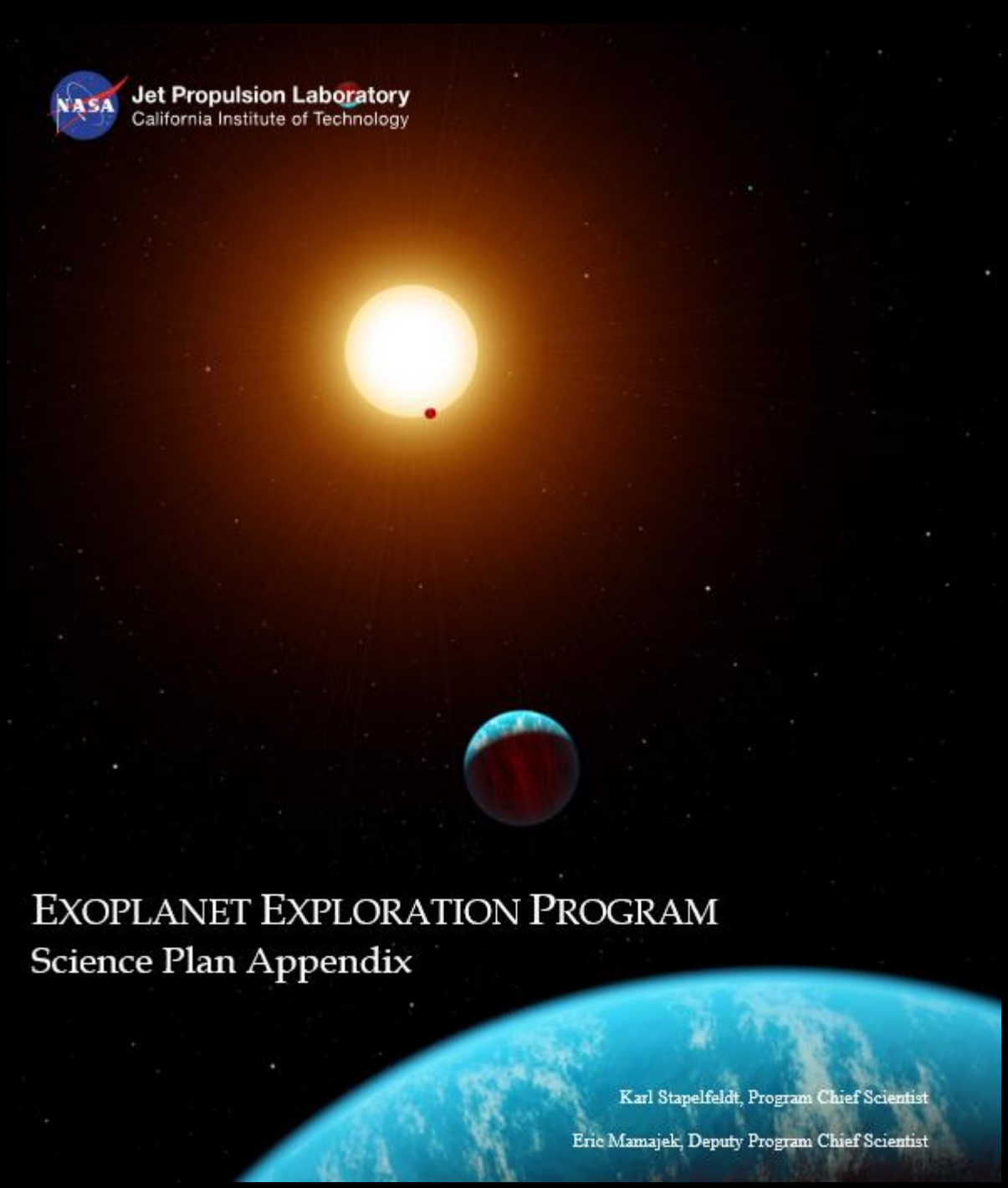
- 5-15 nights per semester over 2-4 semesters
- Must directly support NASA mission science goals
- Important deadlines:
  - Feb. 14: KSMS Notices of Intent due to NExScI
  - Feb. 28: Deadline to request general mission support and KSMS letters from NASA HQ
  - Mar. 14: Proposals due to NExScI

http://nexsci.caltech.edu/missions/KeckSolicitation/

Speckle survey opportunity

Contact steve.b.howell@nasa.gov to get started

- Steve Howell's group at NASA Ames is now funded to support community speckle interferometry observations
- Purpose: deblend host stars of transiting exoplanets so that reliable planetary radii can be derived
- Observations performed for the community and reduced data provided back to the proposer. 100s of targets can be observed in a single night.
- Instruments deployed to Gemini N, Gemini S and WIYN can resolve blends down to diffraction limit and $\Delta V \sim 6$ mag
- Get in touch with Steve to either
  1. Have him add your small target set to his run
  2. Well before the deadline, secure his assistance in preparing your own PI proposal for a large target set


Jet Propulsion Laboratory
California Institute of Technology
EXOPLANET EXPLORATION PROGRAM
Science Plan Appendix
Karl Stapelfeldt, Program Chief Scientist
Eric Mamajek, Deputy Program Chief Scientist

ExEP Science Plan and Science Gap List

- ExEP Science Plan has tactical scope for the implementation of science goals derived by NASA HQ from community policy documents. It now consists of three documents:
  - **The Science Gap List (SGL)**, which specifies areas where additional science work would be beneficial toward achieving Program goals
  - **The Science Development Plan**, which defines roles and relationships between exoplanet scientists at HQ, Program Office, ExEP Projects, NExScI, and ExoPAG. It also lays out the process for SGL updates.
  - **The Science Plan Appendix** provides background information on the state of the field, upcoming missions and facilities, and knowledge needed to inform ExEP objectives in five subdisciplines of exoplanet research. This longer document provides the context for the SGL.
- Version 1.2 is updated to refer to the new NAS Exoplanet Science Strategy report, has been approved by HQ, and will be available soon at https://exoplanets.nasa.gov/science
- The ExEP Science Plan and Gap List may be used in proposal solicitation and evaluation

ExEP Science Gap List as of Fall 2018
(grouped by topic, no implied priority in ordering)

Spectral characterization of small exoplanets
Modeling exoplanet atmospheres
Spectral signature retrieval
Planetary system architectures
Occurrence rates for HZ exoplanets (e.g. $\eta_{\oplus}$)
Yield estimates for exoplanet direct imaging missions
Improve target lists and stellar parameters for exoplanet missions
Mitigate stellar jitter as a limitation to exoplanet dynamical measurements
Dynamical confirmation of exoplanet candidates, determination of their masses & orbits
Precursor surveys of direct imaging targets
Understand the abundance and substructure of exozodiacal dust
Measurement of accurate radii for transiting exoplanets

Final LBTI Science Results

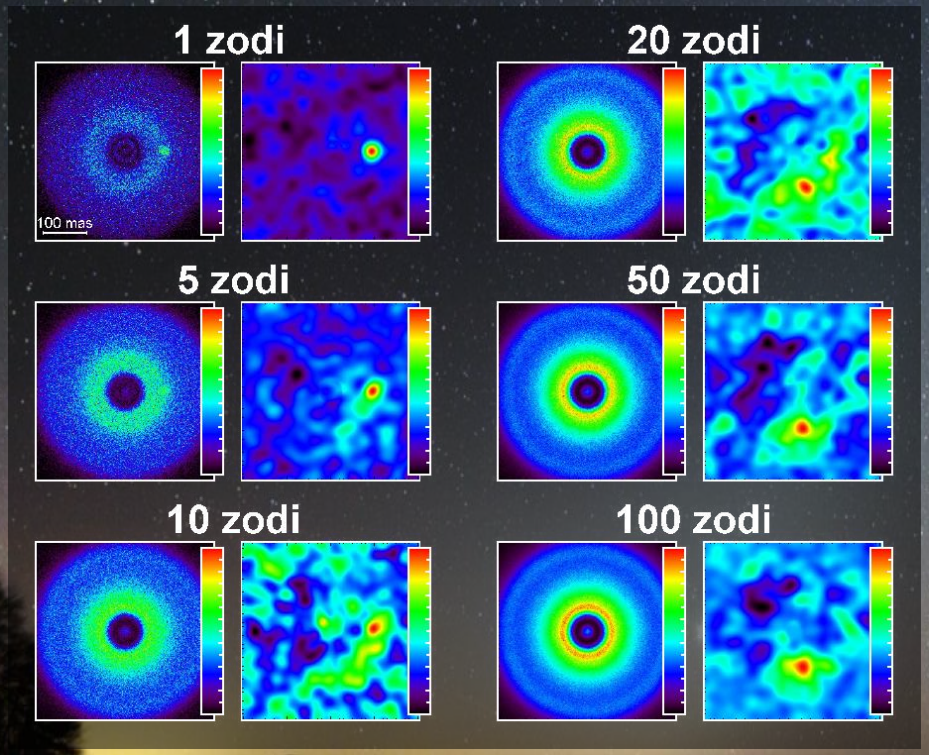
& Implications

With acknowledgements to Steve Ertel,

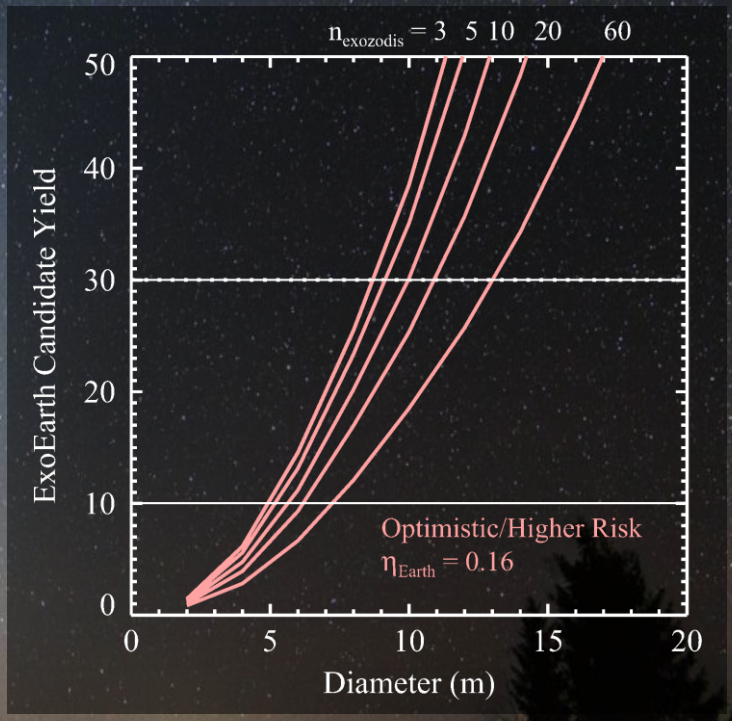
Phil Hinz, and the HOSTS team

Image by Rudi Dobesberger

Levels of warm exozodi affect the yields for future direct imaging of habitable exoplanets (Roberge et al. 2012)



Simulations for 4m telescope, Defrère et al. (2012)

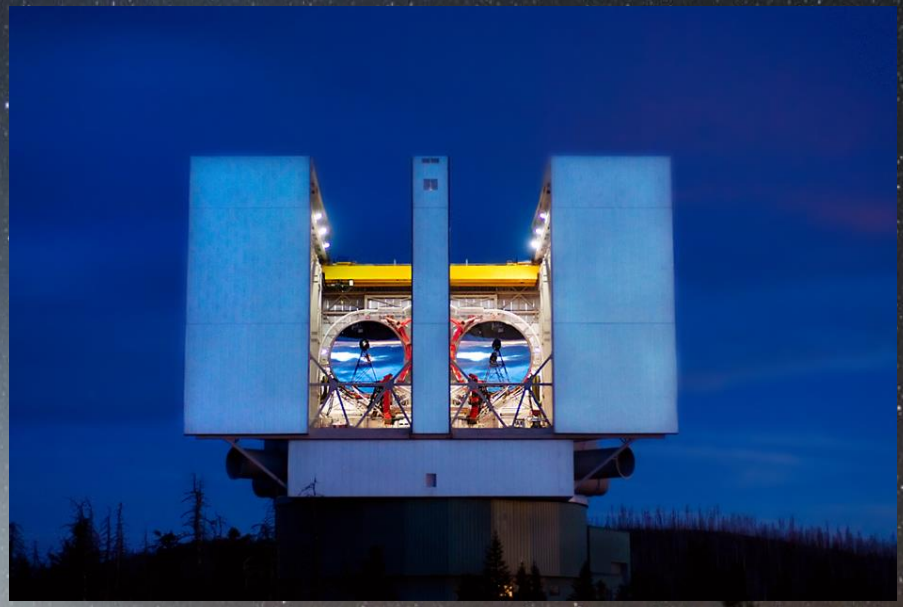


C. Stark et al. (2015, 2016)

Confusion from dust clumps remains an issue but may be solved through synoptic imaging

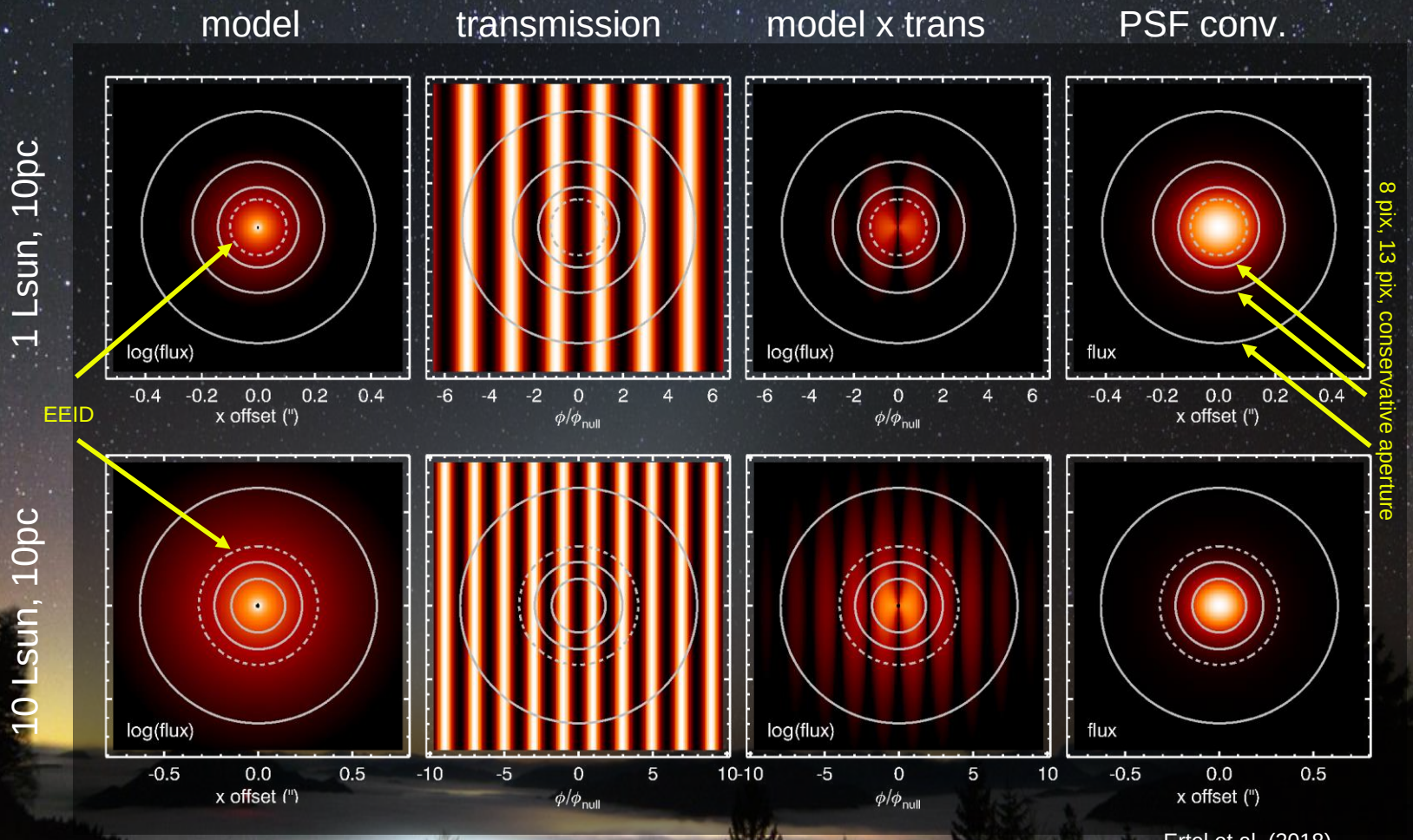
LBT Interferometer at Mt. Graham, Arizona

- Two 8m telescope on common mount, LBTI instrument integral to telescope design, few warm reflections, more optimal 22 m baseline
- NASA-funded key science project “Hunt for Observable Signatures of Terrestrial Systems”, or “HOSTS”, 2012-2018.
- Unbiased survey of 38 stars is now complete. 10 detections, 4 new, and first detections of 10 μm excess around Sun-like stars.



Interim survey results for 30 stars appear in Ertel et al. 2018 A.J. 155 194

How LBTI measures exozodi



Ertel et al. (2018)

Specific stars with LBTI detections

Strong detections	η Crv, β Leo, β UMa, ζ Lep
Sun-like stars	ε Eri, **θ Boo**, 72 Her, 110 Her
Early type stars	Vega, β UMa, **δ UMa**, β Leo, η Crv, ζ Lep
No cold dust	**δ UMa**, **θ Boo**
Also interesting	Vega (little warm dust), τ Cet (no detection)
Weakest detection	Vega, 33 ± 8 zodis

HOSTS results

Table 1: Subsamples, excess detections, and occurrence rates.

	Cold dust	Clean	All
Early type	5 of 6 $83^{+6}_{-23}\%$	1 of 9 $11^{+18}_{-4}\%$	6 of 15 $40^{+13}_{-11}\%$
Sun-like	1 of 2 $50^{+25}_{-25}\%$	3 of 20 $15^{+11}_{-5}\%$	4 of 23 $17^{+10}_{-5}\%$
All	6 of 8 $75^{+9}_{-19}\%$	4 of 29 $13^{+9}_{-4}\%$	10 of 38 $26^{+8}_{-6}\%$

- Probability that stars **with and without cold dust** have the **same occurrence rate of warm dust: $p < 0.003$**
- **New result since interim report:** warm exozodi less common around Sun-like stars than around early types
- N.B. that the HOSTS Survey has **~4x lower sensitivity around Sun-like stars than for Early type stars**

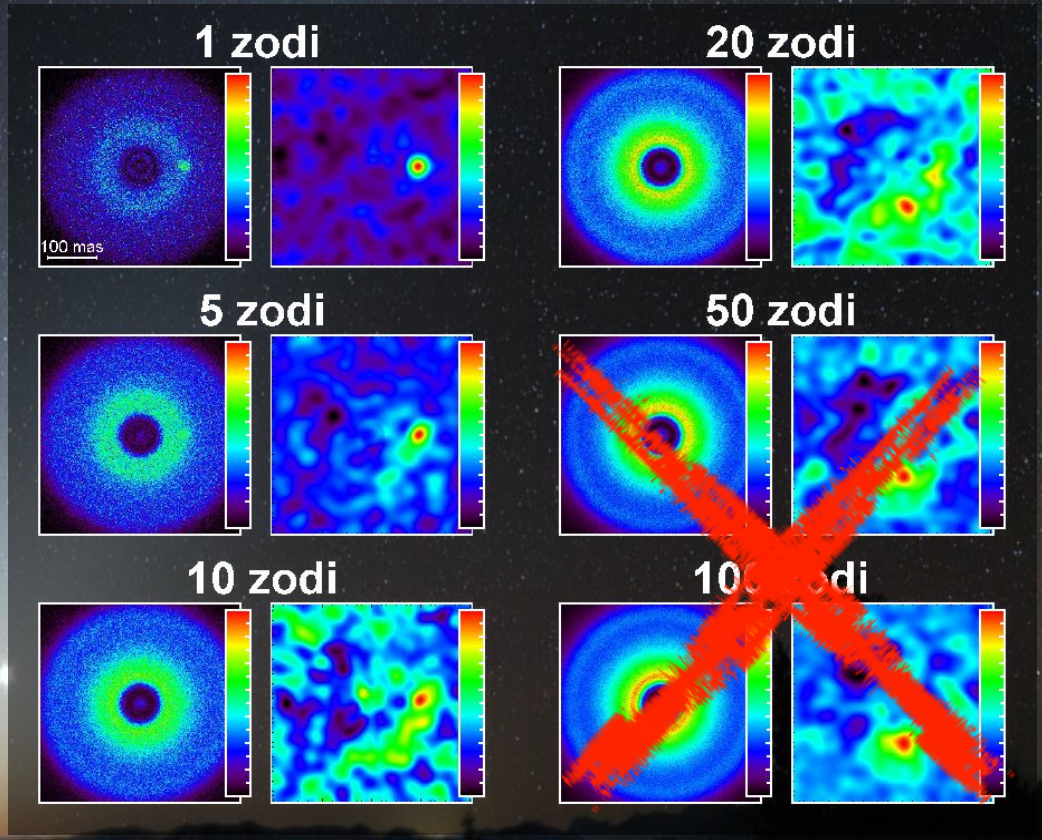
Overall limits to median exozodi level

Upper limits on median zodi level for stars without cold dust (95% confidence, assuming lognormal distribution):

- 13 zodis for all stars,
- 26 zodis for FGK stars

The latter value is most relevant to future direct imaging missions

These limits depend on the assumed distribution function, will be detailed in Ertel et al. 2019



Simulations for 4m telescope, Defrère et al. (2012)

Implications of HOSTS results (1)

- ~ 80% of the stars surveyed lack detectable extended emission at 10 μm, and thus are not very dusty.
- The 26 zodi upper limit on the median exozodi level is a factor of 5 improvement vs. Keck interferometer results. The median exozodi level could still be lower than this.
- The correlation found between HZ dust and cold Kuiper Belt dust suggests that Spitzer & Herschel dust detections can be used to (de)select targets for studies of HZ exoplanets.
- Further observations with an upgraded LBTI, or WFIRST coronagraph imaging later on, could be used to screen more targets and provide more sensitive limits.
- Solar system levels of warm dust remain undetectable at nearby stars

Implications of HOSTS results (2)

- Larger space telescopes can cope better with higher levels of exozodi. At the HOSTS exozodi upper limit, R= 70 spectroscopy of a fiducial Earth analog around a solar analog at 10 pc is
  - Robustly possible with the LUVOIR 8 & 15 m architectures
  - Viable for the HabEx 4m architecture
  - Very difficult for the WFIRST 2.4m architecture. Success would be possible only in the closer and less dusty targets, and by observing at lower spectral resolution.
- Remaining uncertainty in exozodi level implies that integration times needed for detection & spectroscopy will remain uncertain by a factor of several
- For New Worlds mission architectures that are observing time limited, tighter exozodi limits could enable the use of a smaller space telescope.

Jet Propulsion Laboratory
California Institute of Technology

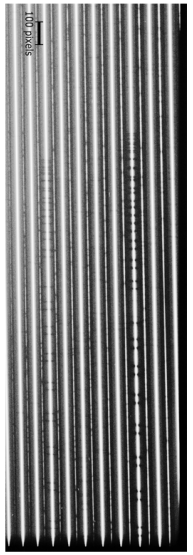
exoplanets.nasa.gov

Acknowledgements

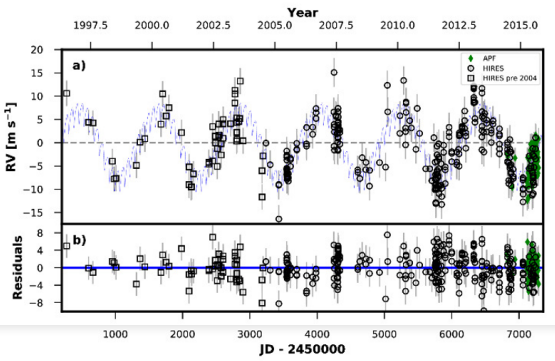
- This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

Update from David Ciardi

Access to Keck HIRES PRV Data Reduction Pipeline



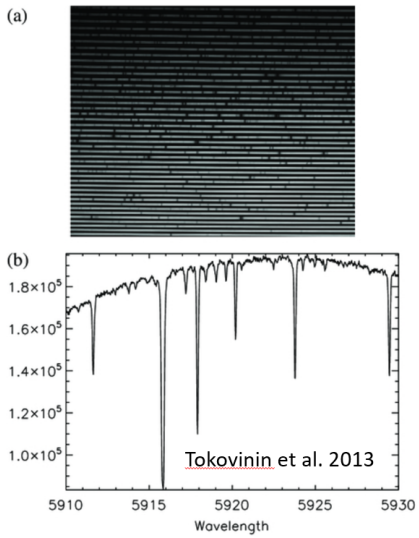
- NASA access to Keck/HIRES currently offers the only precision radial velocity (PRV) capability openly available to the US community
  - NEID becomes operational 2019B
  - NEID complements HIRES: Different Latitudinal Sky Coverage (50% of TESS southern ecliptic sky), Longitudinal Coverage of Orbits, Brightness of targets, Surveys vs Targeted Observations
- NExScI is developing a processing environment for Keck HIRES data in collaboration with the Keck HIRES PRV team at Caltech and WM Keck Observatory (WMKO)
  - Provides a publicly available capability to produce radial velocities at the few m/s level from HIRES data
  - Requires observers follow a specific observing sequence which will be documented at WMKO
  - Builds on the existing IDL software package developed by the California Planet Search team
  - Software will be accessed on a server at NExScI and invoked through a Python interface
  - Uses Python interface to Keck Observatory Archive for data retrieval
- Status
  - CPS software package code delivered and fully operational on NExScI servers
  - Python interface to KOA for data extraction developed
  - Documentation for telescope/instrument set-up and pipeline operations delivered
  - Initial release by Sept 28, 2018 with test data set
- Available for community use in 2019A (see August 15 Call for Proposals)
  - Initial release will work only on data obtained in 2019A and going forward
  - Subsequent release will all allow analysis of earlier data obtained in specified configuration

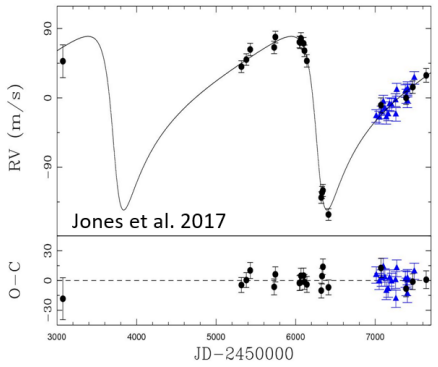


Update from David Ciardi

NASA & NSF Support for US Access to Southern PRV

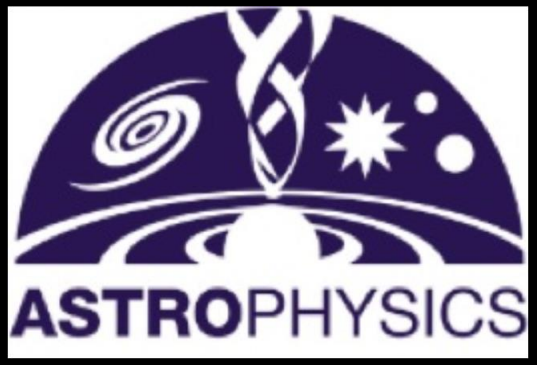
- TESS is performing a (nearly) all-sky search for transiting planets around bright stars
  - Survey starting in the southern ecliptic sky
  - Bright stars enables detailed follow-up and characterization
- PRVs are needed for
  - Planetary masses (and densities): planet demographics, atmosphere characterization
  - Orbital solutions: system demographics, transit and eclipse predictions
  - Binary identification and characterization
  - Spectra for stellar classification
- US community has limited public access to precision radial velocity (PRV) facilities – especially with regards to the southern hemisphere targets.
  - Keck/HIRES and WIYN/NEID have limited access to southern hemisphere
- NASA and the NSF/NOAO have agreed to an augmentation of the existing NN-Explore Program
  - CHIRON on the SMARTS 1.5 telescope
  - ≈>10 m/s precision enables mass determinations of super-earth mass and larger planets (depends on stellar host)
  - 40 nights per semester – augmentation to current NOAO-SMARTS time
  - Queue-mode observations
  - Raw data available through NOAO Science Archive
  - Some data processing through Georgia State University available (1-d wavelength calibrated spectra)
  - Call for proposals will be through NOAO via the NN-Explore Program
  - Starts in 2019A – likely available through 2021A





Staff Changes at NASA HQ

Changes since last ExoPAG



- Astrophysics Division:
  - Paul Hertz, Director
  - Jeff Volosin, Deputy Director
- Exoplanet Exploration Program:
  - Shahid Habib, Program Executive
  - Douglas Hudgins, Program Scientist
  - Martin Still, Deputy Program Scientist
- Astrophyics Strategic Missions Program:
  - Jackie Townsend, Program Manager
  - Tracey Osborne, WFIRST Program Executive